Tribological properties of self-lubricating NiAl/Mo-based composites containing $AgVO_3$ nanowires

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A B S T R A C T

Silver vanadate ($AgVO_3$) nanowires were synthesized by hydrothermal method and self-lubricating NiAl/Mo-$AgVO_3$ composites were fabricated by powder metallurgy technique. The composition and microstructure of NiAl/Mo-based composites were characterized and the tribological properties were investigated from room temperature to 900 °C. The results showed that NiAl/Mo-based composites were consisted of nanocrystalline B2 ordered NiAl matrix, Al_2O_3, Mo_2C, metallic Ag and vanadium oxide phase. The appearance of metallic Ag and vanadium oxide phase can be attributed to the decomposition of $AgVO_3$ during sintering. Wear testing results confirmed that NiAl/Mo-based composites have excellent tribological properties over a wide temperature range. For example, the friction coefficient and wear rate of NiAl/Mo-based composites containing $AgVO_3$ were significantly lower than the composites containing only metallic Mo or $AgVO_3$ lubricant when the temperature is above 300 °C, which can be attributed to the synergistic lubricating action of metallic Mo and $AgVO_3$ lubricants. Furthermore, Raman results indicated that the composition on the worn surface of NiAl-based composites was self-adjusted after wear testing at different temperatures. For example, Ag_3VO_4 and Fe_3O_4 lubricants were responsible for the improvement of tribological properties at 500 °C, $AgVO_3$, Ag_3VO_4 and molybdate for 700 °C, and $AgVO_3$ and molybdate for 900 °C of NiAl-based composites with the addition of metallic Mo and $AgVO_3$.

1. Introduction

Solid lubricants (SLs) are widely used in extreme conditions such as low/high temperatures, vacuum, nitrogen, humid and dry air environment, and among them, the low/high temperatures are the most challenging conditions [1–3]. To overcome the challenge, novel temperature-adaptive composites are developed [4,5]. Those adaptive composites containing binary-lubricant phases or more provide an opportunity to operate over a broad temperature range; the reason may be attributed to the self-adjusted action of the worn surface chemistry and microstructure with temperature. Examples of such composites include $PbO–MoS_2$, $ZnO–WS_2$, and $CaF_2–WS_2$. These binary-lubricant phases are selected due to the fact that MeS_2 lubricant (Me represents for Mo or W element) is benefited for the improvements of the tribological performance at room-temperature (RT), and the formation of $PbMoO_4$, $ZnWO_4$, or Ca_2WO_4 lubricant is suitable for moderate and high temperature lubrication [6–9]. Wear testing results demonstrate that the adaptive composites have excellent tribological properties at a board temperature range. Nevertheless, all these coatings lost their lubricious properties after heating owing to the oxidation of MeS_2 lubricant [10,11]. In addition, those composites are all poor in anti-wear properties due to the absence of hard matrix phase. Thus, how to prepare a material with excellent tribological properties at a wide temperature range attracts many researchers.

Composites such as YSZ–Ag–Mo, YSZ–Ag–Mo–MoS_2, Mo_2N–Ag and Mo_2N–MoS_2–Ag containing hardness and toughness nanocrystalline for wear resistance and complementary solid lubricants for lubrication at low/high temperatures create a basis for the exploration of novel approaches to the board temperature range lubrication [5,12–16]. In those composites, hard nanocrystalline YSZ or Mo_2N phase resists abrasion and fatigue wear in sliding contact, soft metallic Ag is rapidly diffused to the worn surface to act as a moderate-temperature lubricant, and MoO_3 or silver molybdate may be the effective lubricant at higher temperatures. For example, the friction coefficient of Mo_2N–MoS_2–Ag coating is lower than 0.2 at a board temperature range (25–700 °C), which can be attributed to the presence of MoS_2 and Ag lubricant at <400 °C, silver molybdate at 400 °C to 600 °C, and MoO_3 at higher temperatures. Unfortunately, the sublimation of silver molybdate or molybdenum trioxide has an adverse effect on the tribological properties above 700 °C [17].

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Table 1
The density and microhardness of sintered NiAl-based nanocomposites.

Composites	Composition (wt.%)			Vickers hardness	Density (g/cm^3)
	Ni-50 at.% Al	Mo	$AgVO_3$		
NA	100	0	0	549.69	5.69
NAM	92	8	0	624.85	5.88
NAV	85	0	15	521.10	6.07
NAMV	85	8	15	595.73	6.12

More recently, the lubricating effect of silver vanadate is investigated at higher temperatures, hoping to expand the range of temperature (>700 °C) [18–20]. For example, S.M. Aouadi finds that the friction coefficient of VN/Ag coatings could lower to 0.1 at 700 °C, which is attributed to the formation of silver vanadate lubricant. The low friction coefficient of the silver vanadate is associated with the weak Ag–O bonds and characteristic of layered atomic structure. However, the tribological properties of silver vanadate are found to be relatively higher than silver molybdate at moderate temperatures (such as 600 °C) [17,21–23]. Further study of NbN–Ag–MoS_2 coating shows that the friction coefficient is only 0.06 at 750 °C, compared to the 0.27 coating of NbN–Ag, which is due to the self-adjusted action of the worn surface chemistry and microstructure with temperature. For example, the diffusion of silver reduces the friction coefficient at low temperature and the decrease of friction coefficient at high temperature is considered to be due to the formation of silver molybdate and silver vanadate [24]. Nevertheless, the concept of temperature-adaptive lubrication is mainly demonstrated for coating materials, and it may be an effective method to settle the challenge of lubricating at low/high temperature for bulk composites. In this article, self-lubricating bulk composites were designed according to the self-adjusted mechanism to minimize the friction coefficient and wear rate at low/high temperatures.

B2 ordered NiAl intermetallic materials are considered as a potential candidate for high-temperature structural applications due to the attractive physical and mechanical properties, such as high specific strength, high melting point, good thermal conductivity and excellent high temperature oxidation resistance [25–27]. However, the actual use of the NiAl intermetallic as a relative sliding component at high temperatures has been restricted by the severe adhesive wear [28]. The addition of suitable lubricants is an effective way to improve the adhesive wear resistance of NiAl intermetallic at elevated temperatures [29–31]. Thus, the goal of the current article is to provide a comprehensive study of the tribological properties of NiAl/Mo-based composites containing silver vanadate nanowires. It is intended that these composites will provide a self-adjusted action of the composition and microstructure of worn surface to minimize friction as the temperature changes. Nanocrystalline NiAl phase offers good mechanical properties [28,32], and molybdenum and molybdenum carbide improve not only the mechanical properties of composite, but also the oxide of molybdenum, such as molybdenum trioxide. Molybdate acts as an effective lubricant at high temperatures, and silver vanadate nanowires may be the main lubricants at very high temperatures. The design and production of novel temperature-adaptive composites will enable the industry to expand its capabilities to even more extreme conditions.

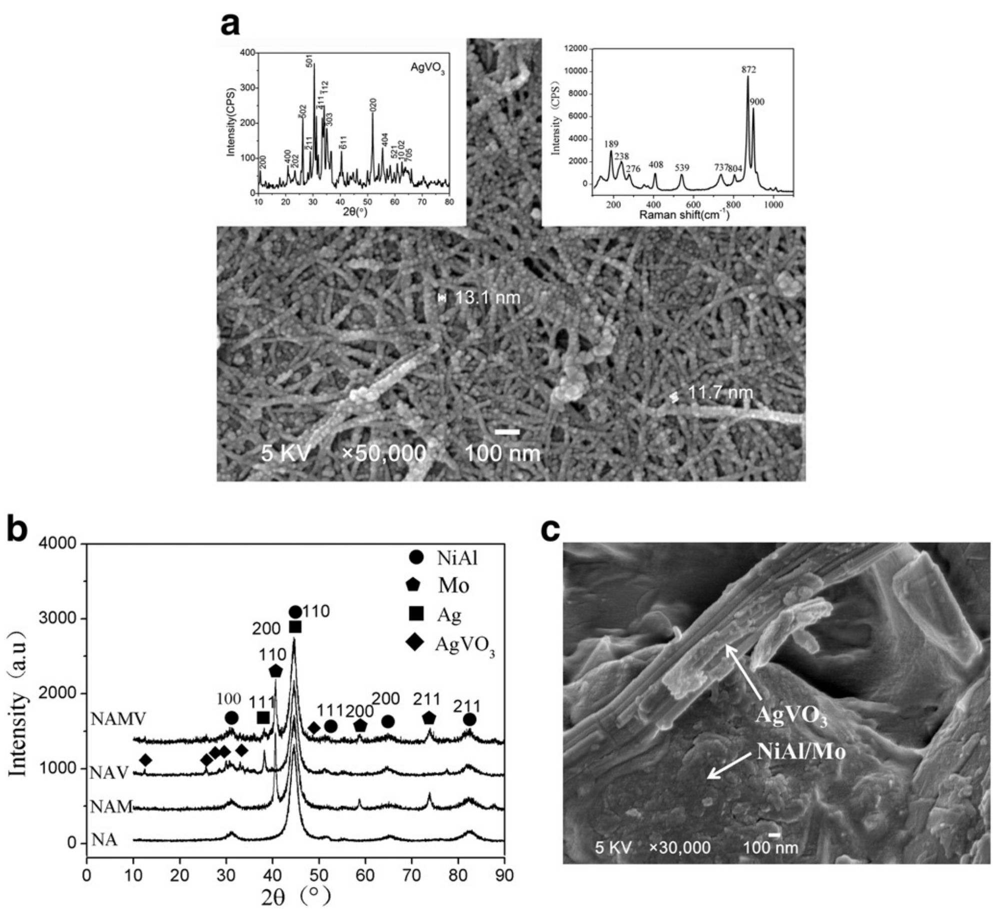

Fig. 1. Characterization of $AgVO_3$ nanowires (a), X-ray characterization of NiAl-based powders (b), and SEM characterization of milled NAMV powders (c).

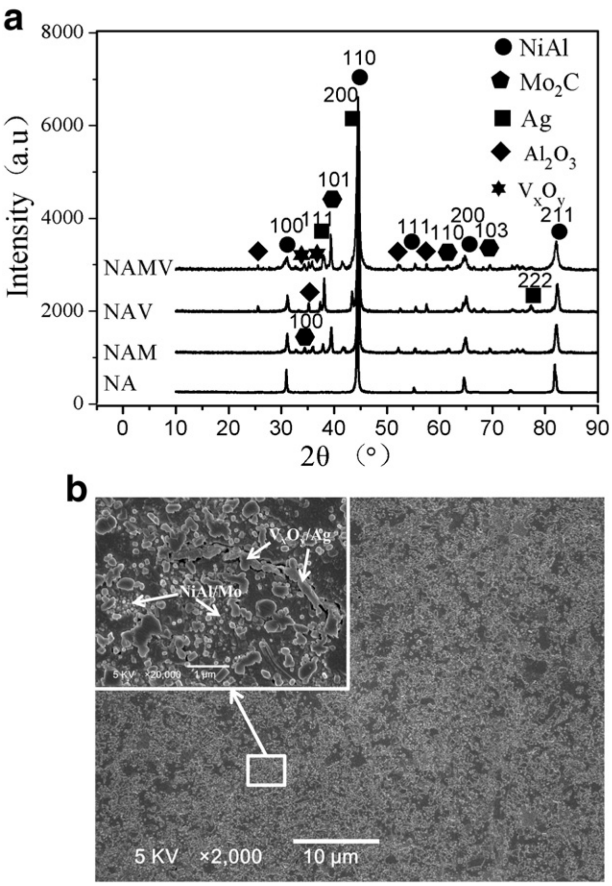

Fig. 2. X-ray diffraction patterns of sintered NiAl-based composites (a), SEM characterization of NAMV composite (b).

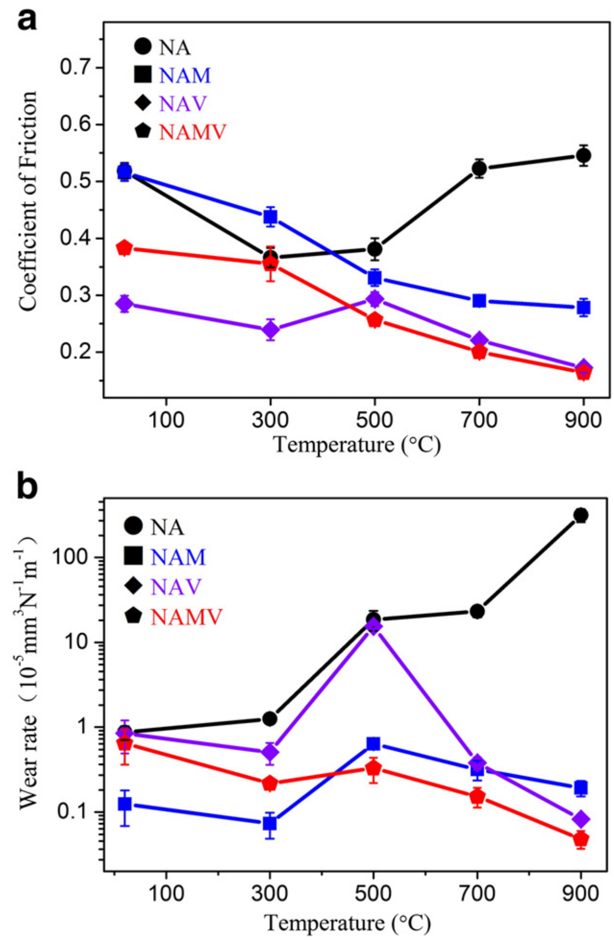

Fig. 3. Friction coefficient (a) and wear rate (b) of NiAl-based composites after wear testing at different temperatures.

2. Materials and Methods

2.1. Preparation of NiAl/Mo-Based Composites

Silver vanadate ($AgVO_3$) nanowires were successfully synthesized by hydrothermal method, and the detailed synthesis process has been reported in literature [33]. NiAl/Mo-based composites containing silver vanadate nanowires were prepared by mechanical alloying (MA) and vacuum-hot-pressing sintering technique. In the NiAl/Mo-$AgVO_3$ system, commercially available powders of nickel, aluminum and molybdenum were mixed to provide a matrix composition of Ni-50 at.% Al or Ni-50 at.% Al/Mo, the detailed contents of composites were shown in Table 1. Ni-50 at.% Al or Ni-50 at.% Al/Mo powders were firstly synthesized by mechanical alloying processes, and then the silver vanadate nanowires were added into the mixed powders for further 5 h ball milling. Finally, the milled powders were enclosed in a graphite die (Ø 24 mm × 80 mm) to be cold pressed under a pressure of 10 MPa and sintered under a pressure of 25 MPa in a vacuum-hot-pressing furnace at 1300 °C for 60 min, followed by furnace cooling (ZT-45-20, Shanghai Chen Hub Electric Furnace Corp Ltd., China). After sintering, the specimens were machined and polished into designed samples for the following analysis and test.

2.2. Characterization

The relative density of sintered NiAl-based composites was measured by the Archimedes method, and microhardness was measured by MH-5-VM microhardness tester equipped with a Vickers diamond pyramid indenter. For each sample, at least ten measurements were carried out using a normal load of 300 g and a dwell time of 5 s, and then the average value of microhardness was listed in Table 1.

The composition and crystal structure of milled powders and sintered composites were characterized by Philips X' Pert-MRD X-ray diffractometer (XRD) with 40 kV operating voltage and Cu Ka radiation in the 2θ range of 10–80°. The microstructure of powders and composites was analyzed by scanning electron microscope (SEM). The tribological properties of sintered NiAl-based composites were performed on a pin-on-disk high-temperature tribometer under ambient conditions at room temperature (RT), 300 °C, 500 °C, 700 °C and 900 °C, respectively. The pin samples were made of sintered NiAl-based composites with a size of Ø 5 mm × 15 mm, and one tip of the pin was prepared to Ø 5 mm hemisphere. The disk samples were made of Inconel 718 alloy with a size of Ø 35 mm × 8 mm. Before wear testing, the specimens were polished by 800 grit emery paper and ultrasonically cleaned in an acetone bath. During wear testing, the upper pin specimen was fixed, while the lower disk specimen was rotated at a linear velocity of 0.287 m/s for 1017 m sliding distance (60 min) at 2 N load. The friction force was continuously measured by a strain-gauge transducer. All the tribological tests were carried out at least three times on the same condition to make sure the reproducibility of the experimental results, and the average results were reported. After wear testing, the specimens were cooled to ambient temperature, and then worn surface was cleaned using compressed N_2 gas. The worn surface morphologies were observed by scanning electron microscope (SEM) and the variations of the phase composition on worn surfaces were investigated by a Renishaw's inVia Micro-Raman spectroscope using a 633 nm wavelength laser light, respectively [34].

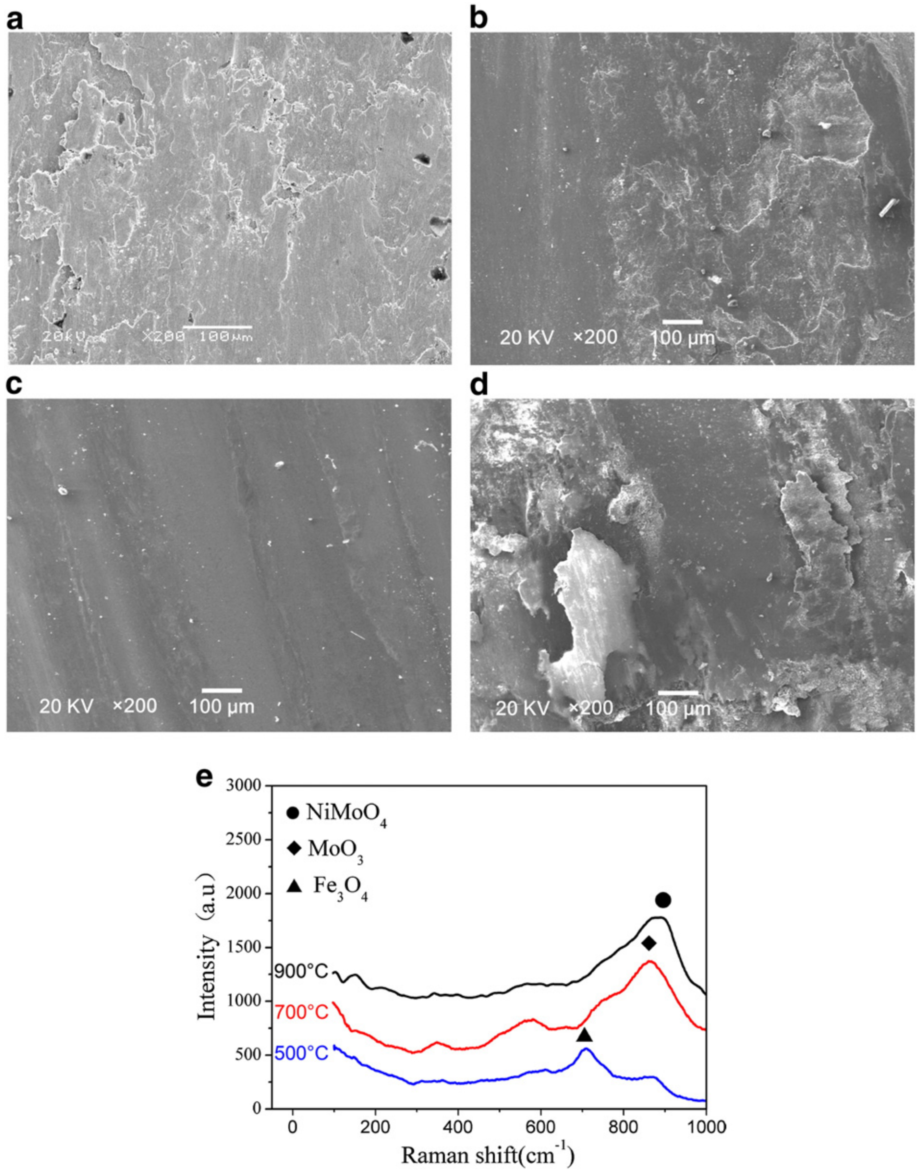

Fig. 4. Worn surface morphologies and composition of NAM composite after wear testing at different temperatures (a) room temperature (b) 500 °C (c) 700 °C (c) 900 °C (e) composition.

3. Results and Discussions

3.1. Material Characterization

Fig. 1 shows the typical XRD pattern and high magnification SEM images of silver vanadate ($AgVO_3$) nanowires and NiAl/Mo-$AgVO_3$ powders (NAMV), respectively. High magnification SEM image (Fig. 1a) reveals that the precipitates synthesized by hydrothermal method are structured with the width about 10 nm. The inset XRD pattern and Raman spectrum results show that the precipitates are β-$AgVO_3$ phases (JCPDS 29-1154) [35]. Subsequently, the crystal structure of NiAl/Mo-$AgVO_3$ powders are characterized by XRD diffractometer, indicating that the milled NiAl-based powders are consisted of nanocrystalline NiAl phase (JCPDS: 44-1188), $AgVO_3$ phase, metallic Ag (JCPDS: 04-0783) and metallic Mo (JCPDS: 42-1120). The appearance of diffraction peaks (100) shows that NiAl phase is B2-ordered structure. Furthermore, the appearance of metallic Ag peaks confirms that $AgVO_3$ nanowires are partly decomposed during the MA process. The morphologies of milled NAMV powders are shown in Fig. 1c, it can be seen that the mixture powders are composed of nanocrystalline NiAl phase (about 30 nm) and reunited $AgVO_3$ nanowires phase with a width of about 100 nm. Thus, XRD and SEM results indicate that nanocrystalline NiAl/Mo-$AgVO_3$ powders are successfully synthesized by mechanical alloying technique.

XRD patterns and high magnification SEM images of sintered NiAl-based composites are shown in Fig. 2. After sintering, XRD results indicant that NiAl-based composites are consisted of NiAl matrix, Mo_2C, Al_2O_3, V_xO_y, and metallic Ag phase. The disappearance of $AgVO_3$ phase and the appearance of metallic Ag and vanadium oxide (V_xO_y) in NAV and NAMV composites suggest that $AgVO_3$ phases are completely decomposed during sintering process. Furthermore, the disappearance of metallic Mo phase and the appearance of Mo_2C precipitates in NAM and NAMV composites can be attributed to the high temperature solid-state reaction of metallic Mo and carbon. Carbon element comes from the methanol during MA process (added to the mixture powder during milling) or the graphite mould during sintering and holding process, which is consistent with the study of Jian Wang and A. Albiter [36, 37]. The microstructure of NAMV composite is further characterized by SEM, as shown in Fig. 2b. Combined with the XRD results, it can be concluded that the sintered NiAl-based composites are consisted of a continuous NiAl intermetallic matrix and zonal precipitates (V_xO_y, Al_2O_3, and metallic Ag). The inset high magnification SEM image indicates

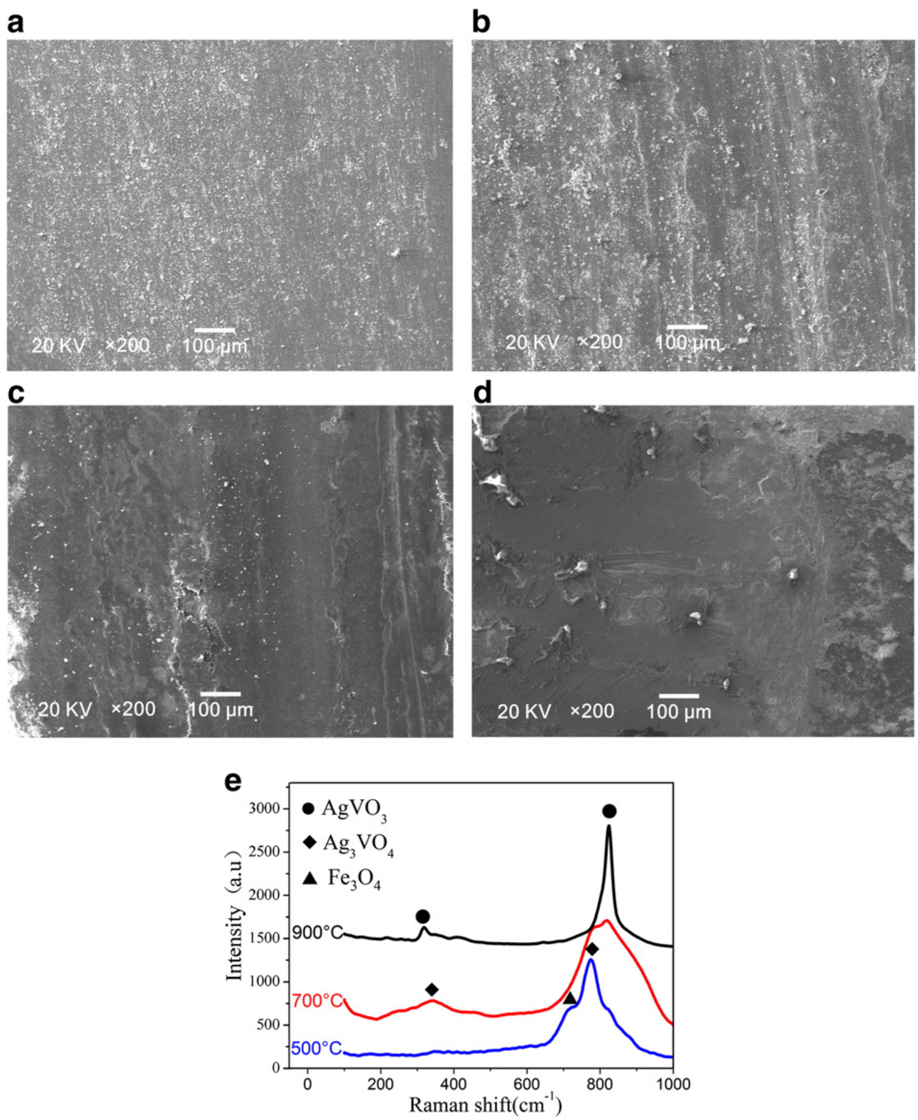

Fig. 5. Worn surface morphologies and composition of NAV composite after wear testing at different temperatures (a) room temperature (b) 500 °C (c) 700 °C (d) 900 °C (e) composition.

that the crystallite size of NiAl phase of is about 100 nm and the width of zonal precipitates is about 500 nm. Thus, XRD and SEM results deduce that nanocrystalline NiAl-based composites are successfully synthesized by hot-pressing sintering technique.

3.2. Mechanical Properties and Tribological Properties of NiAl/Mo-AgVO$_3$ Composites

Table 1 presents the relative density and microhardness of sintered NiAl-based composites. It shows that the density of sintered composites increases with the addition of metallic Mo or silver vanadate ($AgVO_3$) due to the fact that the densities of Mo or silver vanadate are all higher than NiAl phase. The microhardness of sintered composites also increases with the addition of metallic Mo or silver vanadate, but it decreases with the combined effect of metallic Mo and silver vanadate. Two factors are responsible for the change of microhardness: one is the hardening effect of Mo_2C precipitates and fine grain strengthening of nanocrystalline NiAl phase, the other is the weakening effect of soft metallic Ag and V_xO_y precipitates.

The evolution of the friction coefficient (COF) and wear rate of NiAl/Mo-$AgVO_3$ composites is shown in Fig. 3. It can be seen that the friction coefficient of NA composite decreases first and then increases when the temperature is above 500 °C, but NiAl-based composites with addition of metallic Mo or $AgVO_3$ decrease consecutively with increasing temperature except NAV composites at 500 °C. The friction coefficient of NAM composite is higher than NA composite at room temperature and 300 °C, but decreases rapidly when the temperature is above 300 °C. The friction coefficient of NAV composite is lower than NA composite at all test temperatures. The friction coefficient of NAMV composite is significantly lower than NAM and NAV composites when the temperature is above 300 °C, indicating the occurrence of synergistic lubricating effect of metallic Mo and $AgVO_3$ lubricants. Subsequently, the wear rates of NiAl-based composites at different temperatures are shown in Fig. 3b. It indicates that the high temperature wear rates of NiAl-based composites with addition of metallic Mo or $AgVO_3$ are all obviously decreased. For example, at 900 °C, the wear rate of NA intermetallic is higher than $300 \times 10^{-5} mm^3 N^{-1} m^{-1}$ but NAMV composite is only $0.1 \times 10^{-5} mm^3 N^{-1} m^{-1}$, which is also significantly lower than NAM and NAV composites. Similar to the variation of friction coefficient, the wear rate of NAMV composite shows the synergistic lubricating effect of metallic Mo and $AgVO_3$ lubricants when the temperature is higher than 300 °C. Thus, it can be deduced that the addition of metallic

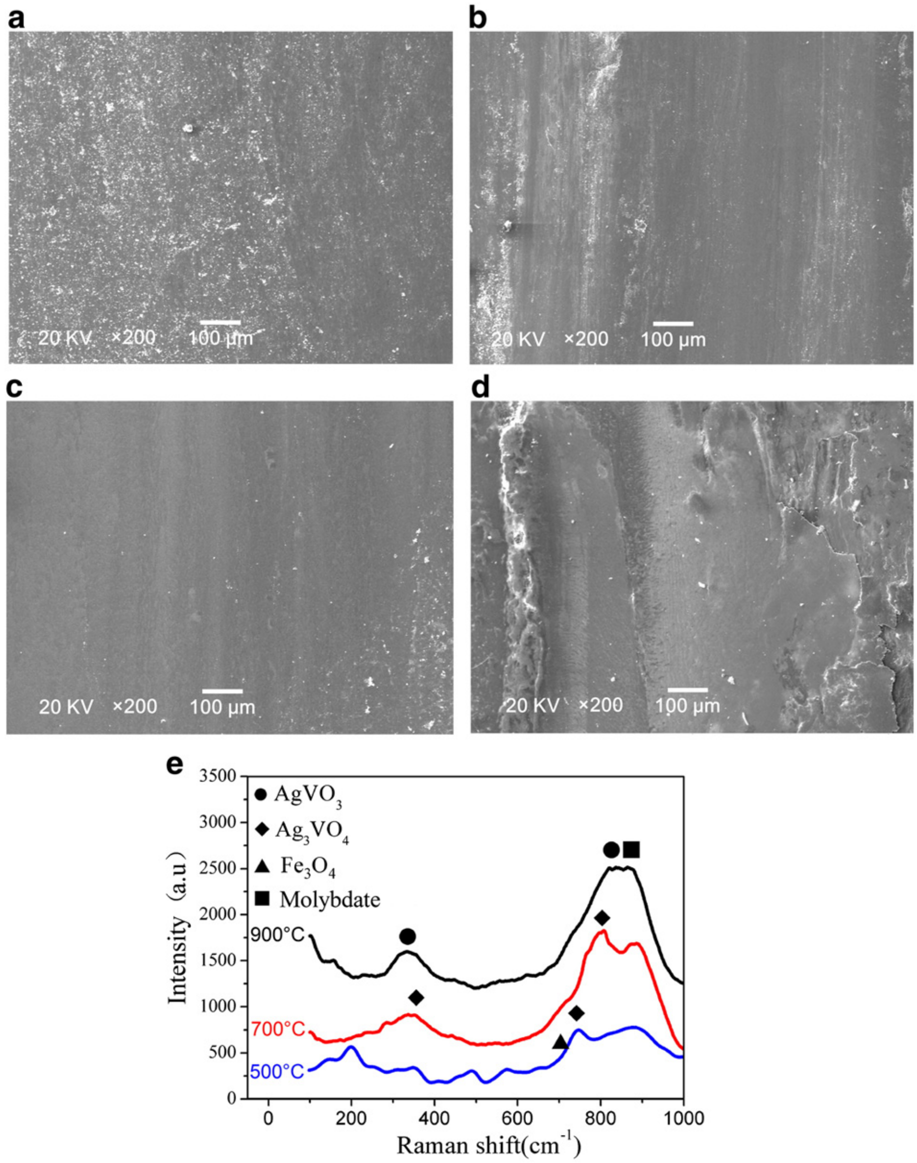

Fig. 6. Worn surface morphologies and composition of NAV composite after wear testing at different temperatures (a) room temperature (b) 500 °C (c) 700 °C (d) 900 °C (e) composition.

Mo and $AgVO_3$ lubricants is beneficial for the improvement of the tribological properties of NiAl-based composites at low/high temperature, especially at high temperatures.

3.3. The Morphologies and Phase Composition of the Worn Surface of NiAl/Mo-AgVO$_3$ Composites

The morphologies and phase composition of the worn surface of NAM composite after wear testing at different temperatures are shown in Fig. 4. At room temperature, larger amount of crack propagations and fractures are found on the worn surface, indicating that the worn mechanism is dominated by adhesive wear (Fig. 4a). At 500 °C, the worn surface is covered by a discontinuous lubricating film accompanied by large fragments, suggesting that the main worn mechanism is plastic deformation and delamination (Fig. 4b). When the temperature increases to 700 °C, a whole scale lubricating film and a small amount of fine groove are present on the worn surface, and the wear mechanism is characterized by plastic deformation and microploughing (Fig. 4c). At 900 °C, it should be noted that a smooth lubricating film containing serious delamination pits is formed on the worn surface of NAM composite during wear testing, demonstrating that the wear mechanism is dominated by delamination and microfracture (Fig. 4d).

The phase composition of the worn surface of NAM composite after wear testing is characterized by Micro-Raman analyzer, as shown in Fig. 4e. The results show that Micro-Raman spectra give better insight into the variations of local phase composition on the worn surface [38]. At 500 °C, Raman spectrum of NAM composite shows that the worn surface primarily consists of MoO_3 and Fe_3O_4. MoO_3 is considered to be an effective high temperature lubricant, thus, the formation of MoO_3 lubricating film is better for the improvements of tribological properties [21,23,39]. At 700 °C, the smoother lubricating film mainly consists of MoO_3, which is benefited for the improvement of the tribological properties of NAM composite. Nevertheless, the sublimation of molybdenum trioxide leads to failure of lubricants when the temperature is above 873 °C [17], and the 900 °C Raman spectrum confirms that the intensities of molybdenum trioxide become weaker but nickel molybdate stronger, demonstrating that the main composition of the lubricating film is nickel molybdate and residues molybdenum trioxide. Thus, it can be deduced that the self-adjustment of the composition and structure of worn surface ensures that NAM composite possesses lower friction coefficient and wear rate at different temperatures.

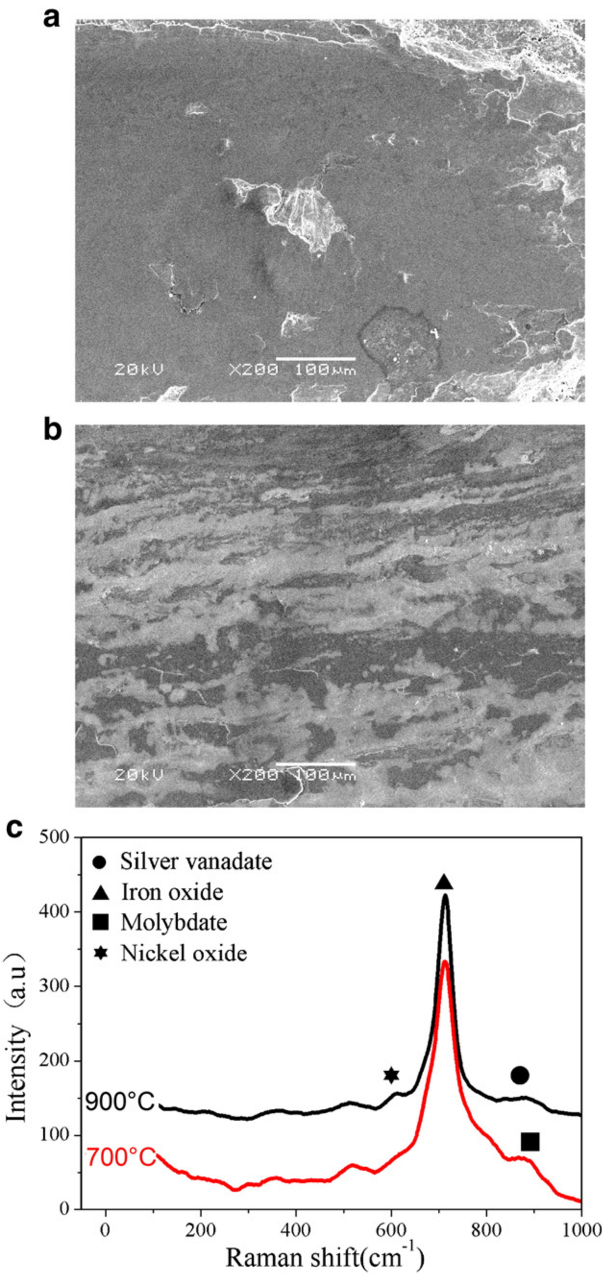

Fig. 7. Worn surface morphologies and composition of Inconel 718 disk against NAMV at 700 °C (a), 900 °C (b) and (c) composition.

SEM micrographs and Raman spectra results of the worn surfaces of NAV composites after wear testing at different temperatures are presented in Fig. 5. Under sliding wear conditions at room temperature, shallow grooves and larger amount of wear debris particles can be seen on the worn surface, suggesting that the wear mechanism is dominant by abrasive wear. The wear mechanism of NAV is obviously different from NAM at room temperature because naturally occurring oxidation films, lubricants and contaminants generally suppress adhesion wear [40]. Thus, the main reason of the different wear mechanism of NAM and NAV can be attributed to the addition of silver lubricants, which can form a lubricating film on the worn surface. At 500 °C, slight scratches and some debris particles are present on the worn surface, implying that the wear mechanism is mainly microploughing (Fig. 5b). In addition, the wear rate of NAV composite at 500 °C is higher than other temperatures, which can be attributed to the existence of metallic silver. The silver presents effectively lubricating function at the temperature below 500 °C, but it is prone to transfer to the counterpart material

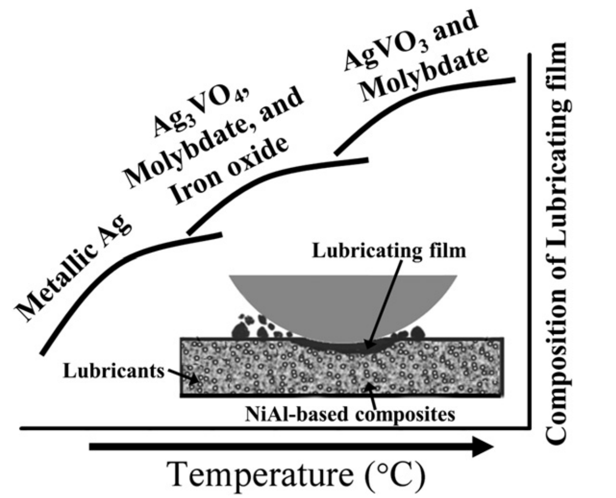

Fig. 8. Schematic of the temperature-adaptive action of NAMV composite at different temperatures.

when the temperature is above 500 °C and accompanied with serious adhesion, leading to the poor tribological properties at 500 °C. At 700 °C, the worn surface is covered by a relatively smooth lubricating film together with some delamination, suggesting that the wear mechanism is dominated by plastic deformation. At 900 °C, a whole scale smoother lubricating film containing some large fragments is formed on the worn surface, indicating that the wear mechanism is plastic deformation and delamination.

The Micro-Raman results of the composition of worn surface after different temperature wear testings are shown in Fig. 5e. At 500 °C, Raman spectrum of NAV composite shows that the worn surface primarily consists of Ag_3VO_4 and Fe_3O_4. Ag_3VO_4 lubricating phase is formed by the tribo-reaction of metallic Ag and V_xO_y, Fe_3O_4 is formed and transformed from the counterpart disk during high temperature wear testing. The formation of oxide film is favorable to the improvement of the tribological properties of NAV composite. At 700 °C, the intensities of Ag_3VO_4 Raman peaks decrease but intensities of $AgVO_3$ increase obviously, which can be attributed to the fact that $AgVO_3$ is more stable than Ag_3VO_4 at high temperatures [19]. At 900 °C, Raman results show that the worn surface consists of $AgVO_3$, Fe_2O_3, and NiO phase. Silver vanadate is well known as an excellent high temperature lubricant [17,19,21], thus, the formation of the oxide film containing silver vanadate on the worn surface is responsible for the decrease of friction coefficient and wear rate [19].

The morphologies and phase composition of the worn surface of NAMV composite after tests at different temperatures are presented in Fig. 6. It can be seen that metallic Mo and silver vanadate lubricants obviously change the morphologies and composition of the worn surface of NMMV composite. At room temperature, shallow grooves and some wear debris particles can be seen on the worn surface, suggesting that the wear mechanism is dominant by microploughing. At 500 °C, it should be noted that a relatively smooth lubricating film and some parallel grooves are presented on the worn surface, implying that the main wear mechanism is plastic deformation and microploughing. At 700 °C, the worn surface is covered by a whole scale lubricating film, demonstrating that the wear mechanism is plastic deformation. At 900 °C, some fragments and delamination pits are formed on the whole-scale lubricating film and the wear mechanism is plastic deformation and microfracture.

The phase composition of the worn surface of NAMV composite after wear testing at different temperatures is evaluated using Micro-Raman spectra analysis, as shown in Fig. 5e. At 500 °C, iron oxide and silver vanadate is the main lubricant on the worn surface. Iron oxide is formed by the oxidation of metallic Fe and silver vanadate is reproduced by the tribo-chemical reaction of metallic Ag and vanadium oxide.

Furthermore, wear testing results show that the friction coefficient and wear rate of NAMV composite is lower than NAM and NAV composites when the temperature is above 500 °C, indicating that metallic Mo and silver vanadate lubricants may form a synergetic lubricating effect. At 700 °C, the intensities of the Raman peaks of silver vanadate (Ag_3VO_4) and molybdate (Ag_2MoO_4 or $NiMoO_4$) decrease but the Raman peaks corresponding to silver vanadate ($AgVO_3$) are detected. At 900 °C, the whole Raman spectra display a peak at the range of 800–900 cm^{-1}, indicating that the worn surface is composed of silver vanadate ($AgVO_3$) and molybdate. Those oxides are responsible for the decrease of friction coefficient and wear rate at high temperatures. Combining the Raman results and tribological properties of NAM and NAV composites, it can be deduced that iron oxide and silver vanadate are suitable for the lubricating effect of NiAl-based composite at 500 °C, molybdate and vanadate for 700 °C or above 700 °C.

3.4. The Morphologies and Phase Composition of the Worn Surface of Inconel 718 Disk Against NAMV Composite

The morphologies and phase composition of the worn surface of Inconel 718 alloy disk against NAMV composite after wear test at 700 °C and 900 °C are shown in Fig. 7, respectively. At 700 °C, it can be seen that the worn surface is covered by a discontinuous lubricating films together with delamination pits, which is responsible for the lower friction coefficient and wear rate. At 900 °C, SEM image shows that the worn surface is covered by a discontinuous lubricating film. Subsequently, the composition of the worn surface of Inconel 718 alloy test against NAMV composite after wear test at 700 °C and 900 °C is characterized by Micro-Raman analyzer, as shown in Fig. 7c. Raman results indicate that the worn surface after wear testing at 700 °C mainly consists of iron oxide and molybdate. Iron oxide is formed by the oxidation of metallic Fe and molybdate is transferred from the pin sample. When the temperature increases to 900 °C, Raman results show that Ag_3VO_4 phase is mainly changed to $AgVO_3$ phase, which is consistent with the composition change of pin samples. The formation of the lubricating film on the worn surface of Inconel 718 disk and NAMV pin is beneficial for improving the tribological behavior of NAMV composites at high temperatures.

It is intended that the excellent tribological properties of NAMV composite at elevated temperatures can be attributed to the fact that NAMV composite can provided a self-adjusted action to minimize friction as the temperature changes. Fig. 8 shows the temperature-adaptive action of the composition on the worn surface of NAMV composite at different temperatures. First, soft metallic Ag is the useful lubricant for wear testing at low and moderate temperatures. The significant decrease of friction coefficients and wear rate of NAMV composite at temperature range of 500 °C − 700 °C can be attributed to the formation of oxide film, such as Ag_3VO_4, molybdate and iron oxide. Finally, $AgVO_3$ and molybdate are the main lubricants at high temperatures. Therefore, it can be proposed that the self-adjusted of the composition on the worn surface remarkably improves the tribological behavior of NiAl-based composites at low/high temperatures.

4. Conclusions

In conclusion, self-lubricating NiAl/Mo-$AgVO_3$ composites were fabricated by powder metallurgy technique and the tribological properties of NiAl/Mo-based composites containing silver vanadate nanowires were tested against Inconel 718 disk from room temperature to 900 °C, the main conclusions can be drawn as follows:

1. NiAl-based composites consisted of B2 ordered nanocrystalline NiAl matrix, Al_2O_3, Mo_2C, metallic Ag and vanadium oxide. The disappearance of $AgVO_3$ and the appearance of metallic Ag and vanadium oxide (V_xO_y) showed that $AgVO_3$ phases were completely decomposed during sintering process.
2. Wear testing results confirmed that NiAl/Mo-$AgVO_3$ composites have excellent tribological properties at a board temperature range. In addition, the friction coefficient and wear rate of NAMV composite is significantly lower than NAM and NAV composites above 300 °C, indicating the occurrence of synergistic lubricating effect of metallic Mo and $AgVO_3$ lubricants.
3. Raman results indicated that the composition and structure on the worn surface of NiAl-based composites were self-adjusted after wear testing at different temperatures, which was the main reason for the improvement of the tribological properties of NiAl-based composites.

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